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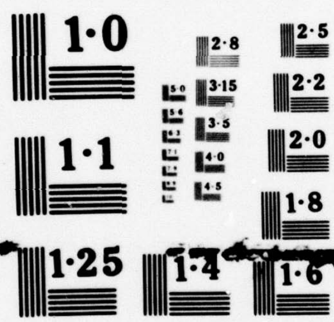

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Bathymetric Effects on Three-Dimensional Ray Traces

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Many ray tracing programs allow for a sloping or structured bottom but completely ignore the fact that the vector normal to the bottom can have an out-of-plane component. To ignore this in long range propagation over irregular bottoms is to assume cylindrical symmetry of the bathymetry about the source, a condition rarely realized in at-sea experiments. This paper describes a preliminary effort to devise and apply a numerical technique to demonstrate the three-dimensional effects of ray tracing over actual seamounts, ridges and basin walls.

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BATHYMETRIC EFFECTS ON THREE-DIMENSIONAL RAY TRACES

INTRODUCTION

Many ray tracing programs allow for a sloping or structured bottom. But when the normal to the bottom is tilted out of the vertical plane, a reflected ray is deviated from a straight line path, as viewed from above. Thus if multiple reflections occur between the sea surface and the bottom, a general curving of the ray path is expected. For low frequencies when the bottom losses are small, this ray curving can persist through many reflections. On the other hand, if the bottom irregularities are pronounced, a few reflections can lead to significant path deviation. To ignore this in long range propagation over irregular bottoms is to assume cylindrical symmetry of the bathymetry about the source so that propagation over a seamount, ridge or trough is really propagation over an annular ridge or trough with its center directly under the source. Likewise, for propagation in basins or continental slope/rise regions where multiple surface-bottom reflections can occur, attention must be paid to the influence of bathymetry on ray paths.

Data from large explosions [1-6] typically contain discrete and continuous arrivals delayed in the order of 10-15 minutes, depending on the size of the basin. In some cases these arrivals come from areas where the bathymetry is more wedge-shaped than wall-shaped (the difference being only the degree of the slope). In those cases it is difficult to determine whether the echoes are due to multiple reflections or by single scattering. Nevertheless, anytime the slope has a component out of the plane of propagation, the heading of the ray path must be expected to change.

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The phenomenon was first dealt with by Weston [7,8] and some of the effects in the vertical plane were investigated later by Milder [9]. Most recently, Harrison [10, 11] has extended these investigations by taking full advantage of multiple-reflection ray-invariants and small angle approximations. This has allowed him to analytically study the effects of simple, symmetrical bathymetry. Since conditions and environments associated with at-sea experiments rarely approach those, it was felt that a numerical technique would be useful in which the effects of actual bathymetry and sound speed profiles could be studied in specific regions of the oceans. This paper discusses such a technique and presents results [5] obtained with it in specific regions of the Norwegian and Greenland Seas, (See Fig. 1).

THREE-DIMENSIONAL RAY TRACING

Since the vector normal to the ocean bottom at the point where the ray is reflected can have a general orientation, the area of study is divided into a rectangular grid. From the bathymetric contours each point is assigned a depth and a two-dimensional index. All necessary information about the bottom is thus derived from these numbers. The index number pairs are either both odd or both even, to simplify the task of keeping track of the triangle containing the propagation ray-head. This is illustrated in the upper left corner of Fig. 2. In general, there are two possible orientations of the triangle, (See Fig. 3). A test is made each time the ray head is incremented to see if the ray has crossed a grid boundary. If the test shows that a grid boundary has been crossed, the program transfers to a section which determines the indices of the new triangle. Control is then transferred back to the main loop and the ray tracing continues. (See Fig. 4.)

The program accepts a layered velocity profile, each layer has a constant sound speed gradient, and at present assumes it is independent of range. As the ray is traced, the program

keeps track of the layer in which the ray head lies and the depths of the turning points, when propagation is in a sound channel.

As shown in Fig. 3, the origin of the surface coordinates is always at the left most vertex regardless of which triangle the ray head is in. If the surface is viewed from above, Z_N is the depth associated with the upper vertex, Z_S the lower vertex, and Z_V remaining vertex of the triangle containing the ray head. Given the point (x, y) within a triangle, the bottom depth at that point is

$$Z = Z_V - \frac{Z_V - Z_N}{\Delta} x - \frac{Z_V - Z_S}{\Delta} y, \text{ when } x + y < \Delta$$

$$Z = Z_V + \frac{Z_V - Z_N}{\Delta} (y - \Delta) + \frac{Z_V - Z_S}{\Delta} (x - \Delta), \text{ when } x + y > \Delta$$

while the vector normal to the bottom is

$$\mathbf{N} = \frac{1}{N} \left(\frac{Z_N - Z_V}{\Delta}, \frac{Z_S - Z_V}{\Delta}, -1 \right), \text{ when } x + y < \Delta$$

$$\mathbf{N} = \frac{1}{N} \left(\frac{Z_V - Z_S}{\Delta}, \frac{Z_V - Z_N}{\Delta}, -1 \right), \text{ when } x + y > \Delta$$

with

$$N^2 = \frac{Z_N^2 - 2Z_N Z_V + 2Z_V^2 + Z_S^2 - 2Z_S Z_V}{\Delta^2} + 1$$

If α is the angle between the bottom normal and the local vertical, and β' the angle between the horizontal projection of the bottom normal and the x axis, then at the point of reflection on the bottom (See Fig. 5)

$$\cos \alpha' = 1/N$$

$$\cos \beta' = \begin{cases} \dfrac{Z_N - Z_V}{N\Delta \sin \alpha}, \text{ when } x + y < \Delta \\[2ex] \dfrac{Z_S - Z_V}{N\Delta \sin \alpha}, \text{ when } x + y > \Delta \end{cases}$$

The new vertical angle γ is given by

$$\sin \gamma = \cos 2\alpha \sin \theta + \sin 2\alpha \cos \theta \cos \beta$$

while the ray heading is changed by the angle ϕ, given by

$$\tan\phi = \frac{\sin 2\alpha \sin \beta [\tan \theta + \cos \beta \tan \alpha]}{1 - \sin 2\alpha \cos \beta [\tan \theta + \cos \beta \tan \alpha]}$$

Also, the statement that the angle of incidence is equal to the angle of reflection is equivalent to the statement

$$\cos \gamma \sin \eta - \cos \theta \sin \beta$$

Ray traces can be generated using Snell's law

$$\cos \theta_{new} = \frac{C_{new}}{C_{old}} \cos \theta_{old}$$

where the sound speed profile has been approximated with horizontal layers of constant-gradient sound speed variation. As the rays are generated, the triangular region below the ray can be kept track of by the triangle indices. When the ray encounters the bottom, the orientation of the bottom normal is obtained from the bathymetric digitization at the triangle vertices. From this the incident ray angles can be obtained which then gives the new ray heading and vertical propagation angle. Then the ray tracing continues with Snell's law, (See Fig. 4).

RESULTS AND CONCLUSION

Specific areas of the Norwegian and Greenland Seas have been digitized and used in the program described. Figure 6 shows the horizontal projections of rays incident into the northeast corner of the Norwegian Sea. The insert on the left shows the velocity profile, the source depth, and the initial vertical ray angle. With this initial vertical angle, the rays propagate in the sound channel until the depth is about 1500 m. Then they begin reflecting between the bottom and surface, changing heading and becoming steeper as the depth decreases. Note that the more the bottom normal is tilted out of the propagation plane, the more curving the ray experiences. Two rays in the center of the pattern encounter the bottom

where the normal is almost in the propagation plane and thus experience little curving as they reflect between the bottom and surface. This causes the reflecting from the northeast corner to be split into two regions. The rays are plotted up to about 45 bottom reflections, at which point most re-enter the sound channel. Some rays virtually get stuck in shallow water experiencing very many bottom bounces; therefore, range may be terminated after a predetermined number of bounces when their remaining energy can be assumed nill.

Sound propagation over submerged seamounts offers a particularly good application for the three dimensional ray techniques. Figure 7 shows the ray paths over Vesteris seamount. The dots represent the point of bottom reflection. Relatively few bounces are required to create a significant divergence of the rays in the horizontal plane. All modeling of the shadowing effect of seamounts which are known to the author have presumed that the two-dimensional models were applicable.

At this time no intensities are calculated in the ray programs to account for the ray divergence or the loss at the bottom reflections. The first objective was to devise a program to study the effects of bathymetry in three-dimensional ray tracing. The ultimate usefulness of the three-dimensional techniques will depend on the development of routines to calculate the intensity field. Nevertheless, this preliminary effort has explicitly demonstrated that important three-dimensional effects can occur when rays interact with bottom areas characterized by significant bathymetric changes such as seamounts, ridges, and basin walls.

ACKNOWLEDGMENT

I should like to thank Dr. C. H. Harrison for many useful discussions.

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Figure 1 — Bathymetry of the Norwegian and Greenland Seas

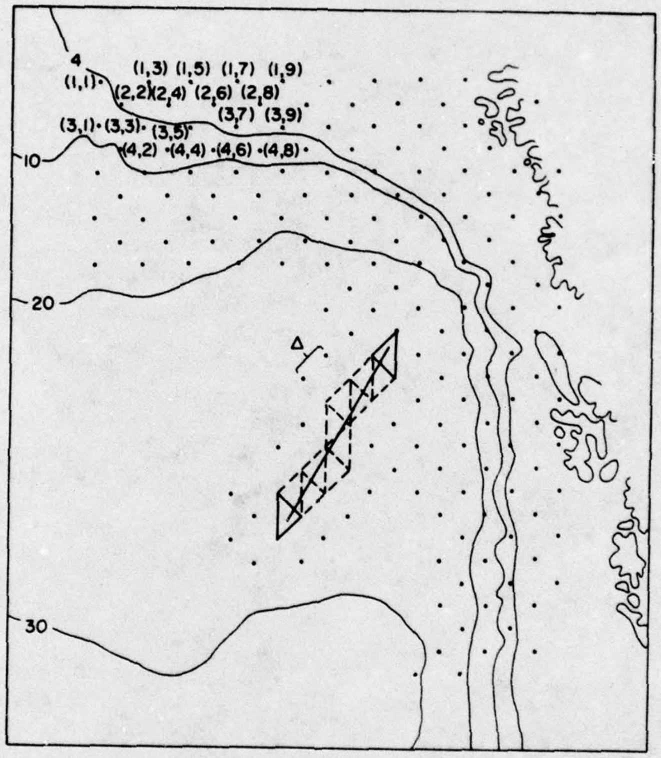

Figure 2 — Digitization of the bathymetry of the NE corner of the Norwegian Sea. Depth contours are in hundreds of meters.

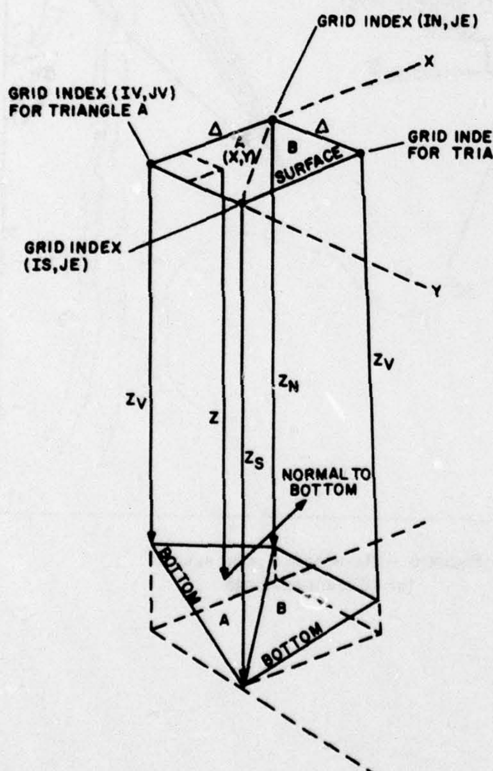

Figure 3 — Geometry of the water column

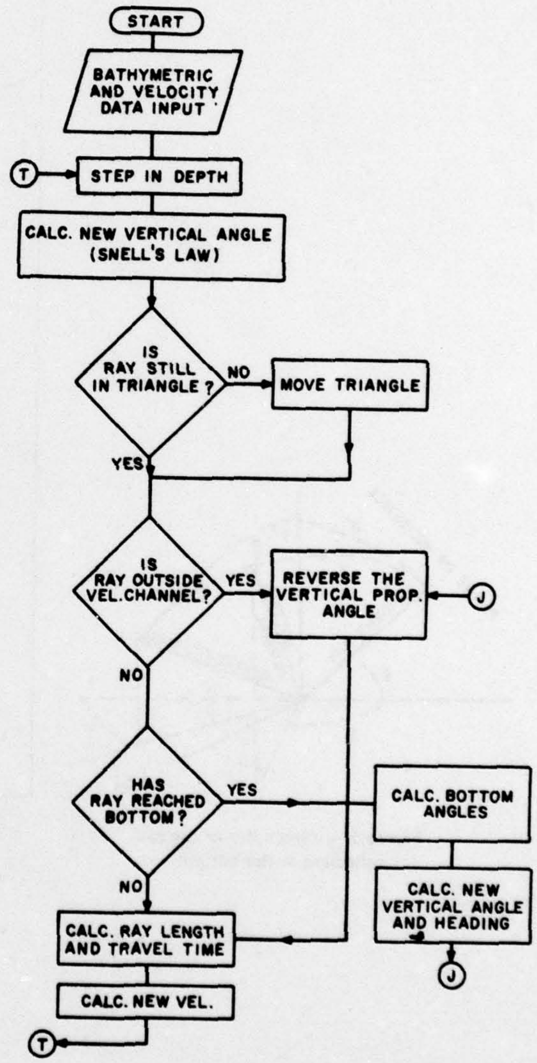

Figure 4 — Flow chart for program logic

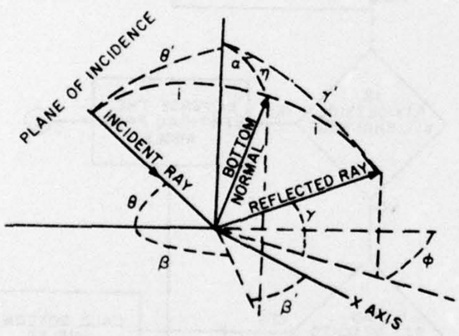

Figure 5 — Geometry of the ray reflection at the bottom

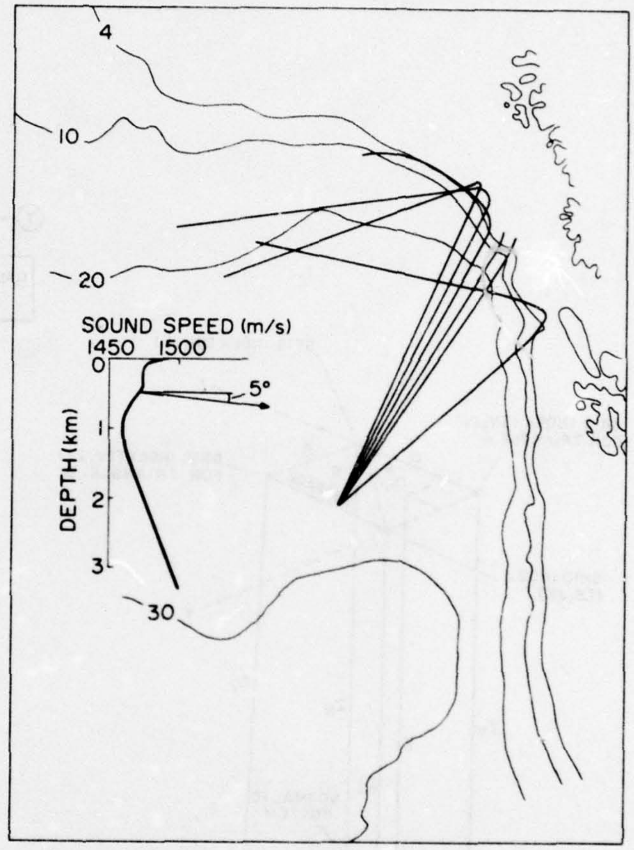

Figure 6 — Rays from a point source for different headings

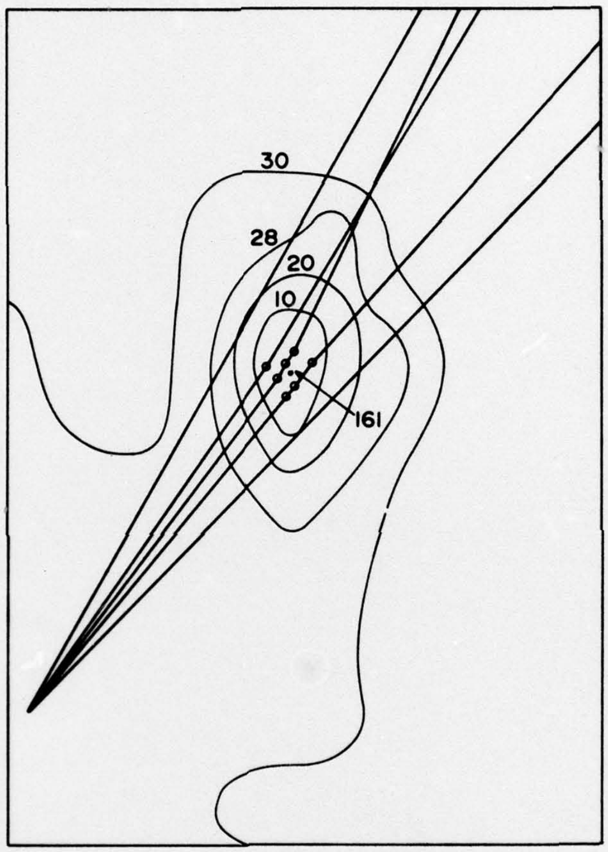

Figure 7 — Ray paths over a Vesteris Seamount (73°N 18°W). The ● denote bottom reflections.